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Numerical study on transverse temperature distribution of fire zone in metro tunnel fire

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Abstract

To study transverse temperature distribution of fire zone in subway fire, an entity tunnel model is established by fire dynamics simulation software FDS to simulate transverse temperature distribution away from fire source 0 m, 0.5 m in different fire powers. The results showed that: fire power is closely related to the temperature of the surface of the lining, the greater the power, lining temperature higher at the same location. At the same time the highest temperature of lining in the fire zone is in the top, followed by bottom, the lowest central. So we should thicken the thickness of the protective layer of reinforced in the top during tunnel construction and anti-fire design, at the same time, cabling should be possible to set up in the central to prevent heat damage. A fitting formula determining the transverse temperature distribution of radiation zone and convection zone was developed by the dimensionless temperature treatment. It has high accuracy and mostly within 10% error, can be well applied into engineering.

Keywords: metro tunnel; fire; fire zone; transverse temperature; numerical simulation

Nomenclature

D^*	characteristic diameter of fire(m)
Q^*	heat release rate (kW)
g	gravitational acceleration（m/s^2）
T_a	initial environment temperature (℃)
C_p	specific heat of air （J/(kg·K)）
Δx, Δy, Δz	grid size(m)
R*	reference value
T	smoke temperature (℃)
t	burning time of fire(s)
t_0	time of fire reach to 1 MW(s)
a	radian of lining surface and ground axis
$T_{max,0}$	maximum value of fire smoke temperature away from fire source 0 m
$T_{max,0.5}$	maximum value of fire smoke temperature away from fire source 0.5 m
Greek symbols	
α	fire source development coefficience

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ρ_a	air density（kg/m^3）

1. Introduce

With the rapid development of China's economy, transport services also present flourishing and many metros appeared in people's lives. Since the tunnel buried deep in the ground, a lot of smoke and heat from fires difficult to discharge, resulting in a sharp rise in the tunnel temperature, seriously affect the safety of personnel evacuation and structural stability. Smoke temperature is closely related to temperature rise of tunnel lining and structural stability, so it's important to get the smoke temperature distribution before analyzing the destroy of tunnel structure. At present, domestic and foreign experts mostly heating the tunnel lining by using RABT, Runehamer, HC, RWS, and ISO 834 [1,2,3,4], but these temperature curve can only reflect the changes of temperature with time, ignoring the spatial temperature variation. Figure 1 shows that lining temperature are subject to smoke thermal convection and fire thermal radiation, which result in non-uniform temperature distribution. This non-uniform transverse temperature tends to produce more damage stress and threaten the structural stability of the lining. However, there is few research on the transverse temperature distribution of fire zone, mostly concentrated on maximum smoke temperature and longitudinal induced t smoke temperature under the ceiling. Therefore, this article will simulate transverse temperature distribution characteristics of fire zone in different fire scenarios in order to provide a reference for tunnel fire protection design.

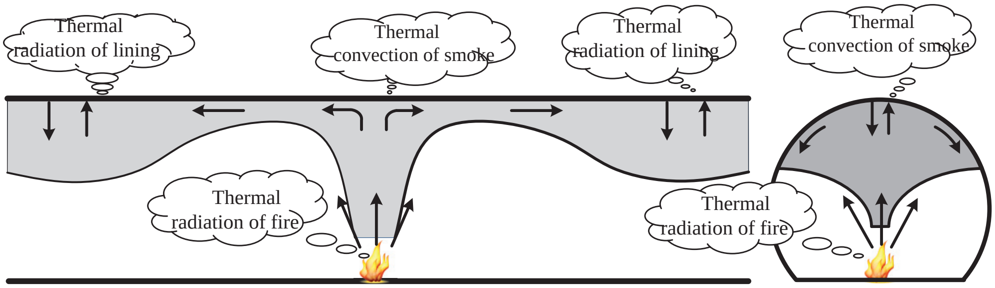


Fig1 Heat transfer process of metro tunnel fire

2. Numerical Simulation Study

Numerical simulation is an effective way to study tunnel fire, because it can not only save resources, but also rule out outside interference of full-size and large-scale test to easily meet experimental conditions. For example, Chen [5] studied the situation of the tunnel temperature distribution and smoke flowing through the FDS simulation and experimental methods. Wei Zhong [6] studied the longitudinal temperature distribution of tunnel fire through FDS. Fang Liu [7] used FDS simulation and experimental methods to study the maximum smoke temperature under the ceiling and found a good matching degree between simulation and experimental results. The results above show that the simulation have a high accuracy and can effectively simulate smoke flow and heat transfer processes in tunnel.

2.1. Model and parameter settings

Figure 2 is a simulation test model based on the entity metro tunnel, length of 5.0 m, concrete lining with a thickness of 0.25 m, a thermal conductivity of 1.28 W/m·K, a density of 2200 kg/m3, a specific heat capacity of 0.88 KJ/(kg·K), an initial temperature of 20 ℃, a pressure of 101.3 kPa. 112 thermocouples are set away from fire source 0 m and0.5 m. The thermocouple intensity of the top twice the bottom because of the large temperature gradient of top.

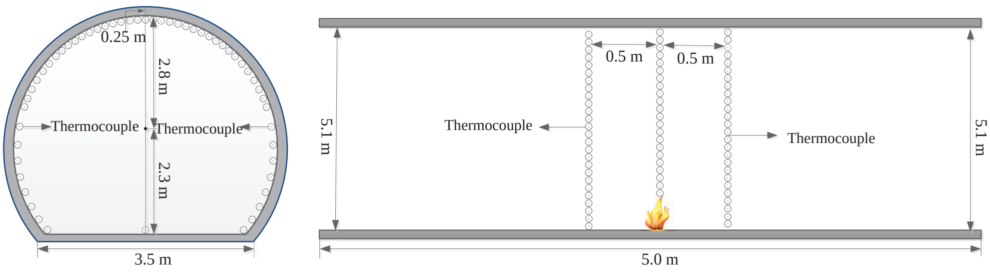


Fig 2 Schematic model of metro tunnel

2.2. Grid Settings

Currently, RANS and LES are widely used in the flow field numerical calculation. This article intends to adopt LES numerical analysis method, because model RANS has a defect in computing the transient of flow field. The grid is a key factor affecting the accuracy of the simulation results in LES simulation [8,9]. Fire Dynamics Simulator User's Guide [10] suggest that an non-dimensional expression R^* relating the grid size of Δx , Δy and Δz with a characteristic fire diameter D^* should be considered. Note that D^* is given as:

$$D^* = \left(\frac{Q^*}{\rho_a C_p T_a \sqrt{g}} \right)^{2/5} \tag{1}$$

$$R^* = \max\left(\Delta x, \Delta y, \Delta z\right) / D* \tag{2}$$

The study found that CFD simulation can well calculate smoke flow rate and temperature issues when R * range from 0.05 to 0.2. Considering the source of fire power in this paper about 5MW, so using a grid system of 0.25 m × 0.25 m × 0.25 m . Figure 3 and Figure 4 show the situation of time step and max CFL number in this grid system. From the figure, CFL number is always hovering at 0.9 and less than a predetermined convergence threshold value. It keeps a high simulation accuracy and speed. At the same time step is about 0.0025 s, so that the grid system can be used for subsequent simulation.

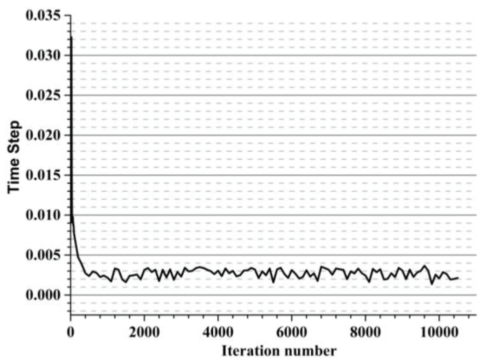


Fig 3 Changes of time step during the simulation

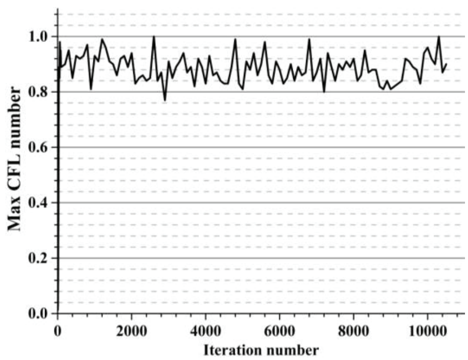


Fig 4 Changes of convergence during the simulation

2.3. Fire setting

A large number of fire cases and experiments show that the source of the fire heat release rate is constantly changing, roughly exponential growth trend with time. It's usually called t^2 fire ignition sources. Ignition sources of fire can be spark, flames, smoldering fires and other types of heat equipment. Ignition sources of fire can be spark, flames, smoldering fires and other types of heat equipment. The power calculations often begin with fuel efficient combustion, regardless of smoldering processes. So the exponential growth of the fire source power can be expressed as [11]:

$$Q^* = \alpha t^2 \tag{3}$$

Fire source roughly divided into slow, medium, fast and very fast according to NFPA [12]. Table 1 shows an example of the relationship between materials and ignition sources development coefficient.

Table1 The relationship between materials and fire development coefficient

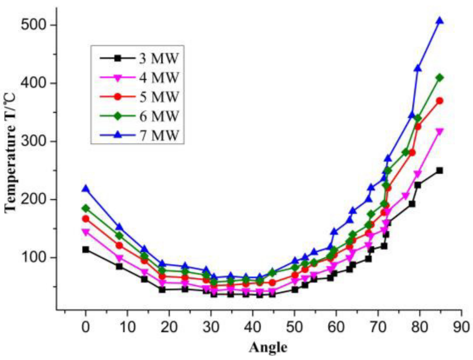
Combustibles	Growth rate	α /(kW/s^2)	t_0 /s
furniture made of wooden planks	slow	0.0029	584
polyester mattress / no cotton products	medium	0.0117	292
plastic foam /pouch filled with mails	fast	0.0469	146
pool fire / upholstered chair	very fast	0.1876	73

The report of China's Rail Transit Project Safety Assessment shows that the rate of heat release metro fire is about 6.8 MW, and with the fast rate to grow. However, the combustibles have been significantly reduced with the continuous development of the metro manufacturing sector in recent years. For example, the fire power of Hong Kong's new airport subway line has been reduced to 5 MW [13]. Therefore, this paper intends to use 3 MW, 4 MW, 5 MW, 6 MW, 7 MW to simulate transverse temperature distribution of fire zone in metro fire.

3. Simulation results and analysis

3.1. Transverse temperature distribution

The temperature of fire zone will keep a relatively stable state after the initial rise. Therefore, this article intends to adopt the highest stable temperature of the measuring point for analysis. Show as Fig 5 and Fig 6.



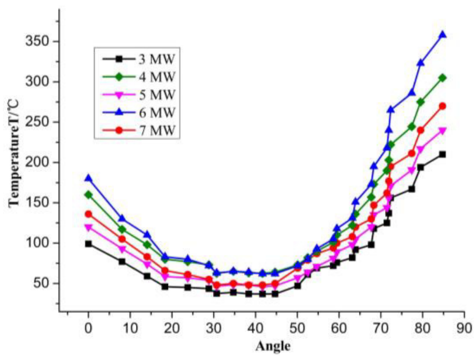


Fig 5Transverse temperature distribution away from fire source 0 m Fig 6 Transverse temperature distribution away from fire source 0.5 m

Fire power is closely related to the temperature of the surface of the lining, the greater the power, surface temperature higher at the same location. At the same time the highest temperature of lining in the fire zone is in the top, followed by bottom, the lowest central. This is because the top is wrapped in smoke and affected by thermal convection. At the same time, the fire thermal radiation has a greater impact on the temperature of bottom. In order to study the transverse distribution of temperature in fire zone, the section is divided into the radiation zone and convection zone.

3.2. Transverse temperature distribution of the radiation zone

To eliminate the effects of fire power on the temperature, the temperature distribution of the radiation zone is dimensionless processed. Show as Fig 7 and Fig 8.

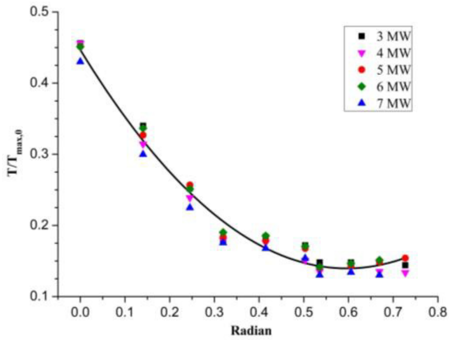


Fig 7 Transverse dimensionless temperature distribution of the radiation zone away from fire 0 m

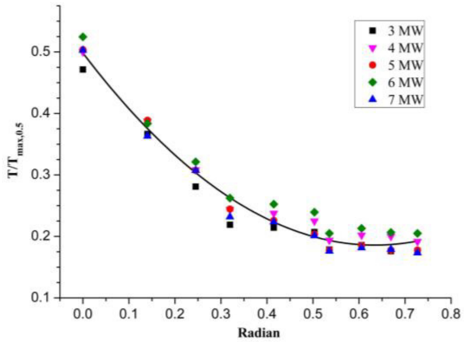


Fig 8 Transverse dimensionless temperature distribution of the radiation zone away from fire 0.5 m

Since the temperature distribution of the radiation zone is mainly affected by the fire radiation. The closer from the fire source, the higher the temperature. Transverse temperature distribution under different power were binomial fit and the coefficients are shown in Table 2. The average values of a, b and c are calculated and substituted into binomial to gives:

$$T / T_{\max,0} = 0.865a^2 - 1.031a + 0.4468 \tag{4}$$

$$T / T_{\max,0.5} = 0.7759a^2 - 0.9847a + 0.4983 \tag{5}$$

Table 2 Fitting results of simulations for the radiation zone.

Distance from the fire /m	HRR/MW	a	b	c	R^2
	3	0.8404	-1.0245	0.4554	0.9806
	4	0.8733	-1.0512	0.4484	0.988
0	5	0.8672	-1.0337	0.4512	0.9882
	6	0.8759	-1.0355	0.4537	0.9879
	7	0.8683	-1.0095	0.4254	0.9901
	3	0.7604	-0.9481	0.4719	0.9826
	4	0.7642	-0.9655	0.4997	0.986
0.5	5	0.7762	-1.0115	0.5064	0.9936
	6	0.7817	-0.984	0.5158	0.987
	7	0.797	-1.0143	0.4976	0.9892

3.3. Transverse temperature distribution of the convection zone

Also the temperature distribution of the convection zone is dimensionless processed. Show as Fig 9 and Fig 10.

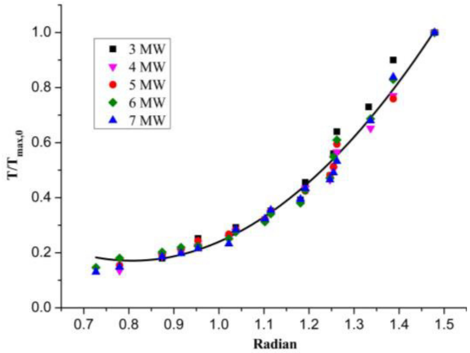


Fig 9 Transverse dimensionless temperature distribution of the convection zone away from fire 0 m

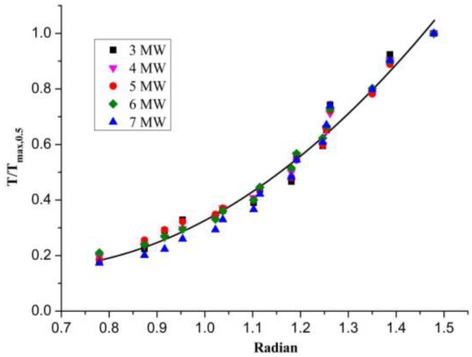


Fig 10 Transverse dimensionless temperature distribution of the convection zone away from fire 0.5 m

$$T / T_{\max,0} = 1.852a^2 - 2.99a + 1.378 \tag{6}$$

$$T / T_{\max,0} = 1.2144a^2 - 1.5106a + 0.6224 \tag{7}$$

Table 3 Fitting results of simulations for the convection zone.

Distance from the fire /m	HRR/MW	a	b	c	R^2
0	3	1.8788	-2.9952	1.3616	0.9777
	4	1.8406	-3.0034	1.3939	0.9906
	5	1.8291	-2.9914	1.404	0.9905
	6	1.8815	-3.0507	1.4063	0.9856
	7	1.8293	-2.9236	1.3201	0.988
0.5	3	1.2049	-1.491	0.6157	0.9734
	4	1.2069	-1.5082	0.6315	0.988
	5	1.1947	-1.5137	0.6551	0.983
	6	1.2065	-1.5001	0.6278	0.9861
	7	1.2592	-1.5398	0.5821	0.9797

Lining surface temperature increases with height rising. The reason for this phenomenon is that the temperature distribution of the convection zone is mainly affected by smoke thermal convection. The higher the smoke temperature, the higher the temperature of the surface of the lining. Transverse temperature distribution under different power were binomial fit and the coefficients are shown in Table 3. The average values of a, b and c are calculated and substituted into binomial to gives:

3.4. Error Analysis

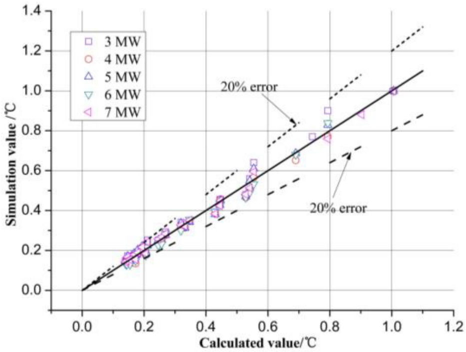


Fig 11 Comparison for the numerical simulation and calculated temperature away from fire source 0 m

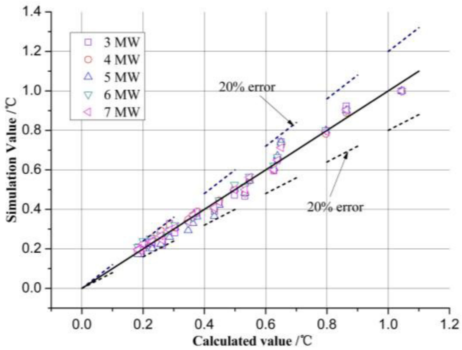


Fig 12 Comparison for the numerical simulation and calculated temperature away from fire source 0.5 m

In order to verify the correctness of the fitting formula, now compared the fitted values with the analog value, the result s are shown in Fig. 11 and Fig. 12. The analog values of the fire temperature were close to the value calculated by the formu la, with little error less, mostly less than 10%. So the formula can be well predicted the distribution of fire lateral temperatur e of the tunnel fire.

4. Conclusion

(1) Fire power is closely related to the temperature of the surface of the lining, the greater the power, surface temperature higher at the same location. Therefore, we must strictly control the fire load of tunnels and metro to protect the structural safety.

(2) The highest temperature of lining in the fire zone is in the top, followed by bottom, the lowest central. So we should thicken the thickness of the protective layer of reinforced in the top during tunnel construction and anti-fire design. At the same time, cabling should be possible to set up in the central to prevent heat damage.

(3) Since the temperature distribution of the radiation zone is mainly affected by the fire radiation. The closer from the fire source, the higher the temperature. By dimensionless processing temperature, which in turn obtained by fitting the temperature distribution equations in radiation zone. The equations have a high accuracy to meet the requirements of engineering applications.

(4) The top of tunnel is wrapped in smoke and affected by thermal convection. The higher the smoke temperature, the higher the temperature of the surface of the lining. Also the temperature distribution of the convection zone is dimensionless processed and binomial fit. It has high accuracy and mostly within 10% error, can be well applied into engineering.

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